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1.1 Introduction

The VIRGO investigation (Variability of solar IRradiance and Gravity Oscillations) on the SOHO mission (SOlar and Heliospheric Observatory) has by now, the beginning of 2002, operated successfully for more than 6 years. The scientific goals of the proposed VIRGO II+ experiment coincide perfectly with those of highest priority in the AO for the Solar Dynamic Observatory (SDO). Don't think that this is true. Only the TSI measurements and their possible role on global change/climate (cf my e-mail from 14 April). This offers the unique opportunity to base our proposal on an existing spare instrument, that has already proven its excellent performance, combined with an upgrade of the Luminosity Oscillation Imager to a LOI+, by significantly improving its imaging capabilities. This mainly to address specific questions related to spatially resolved observations combined with highest photometric accuracy. Thus, we call the proposed experiment: *VIRGO II+*.

I think this first paragraph needs to be re-written, perhaps by a native speaker?

Background: More than two decades of observations have shown the solar irradiance to be changing at all wavelengths. Proxy studies have suggested that solar variability could be on the verge of producing significant terrestrial climate change (Hansen et al. 1993; Lean et al. 1995; Crowley and Kim 1996; Reid 1991; 1997; White et al. 1997; Solanki and Fligge 1998). Studies of variability in other solar-type stars implies the possibility of larger total solar irradiance fluctuations, perhaps in the range of 0.4–0.7% (e.g. Nesme-Ribes et al. 1994; Zhang et al. 1994; IPCC 1995 Report), significantly greater than the current 0.1% variation observed over the last solar cycles. Furthermore, the well documented Maunder minimum in the late 1600's (Eddy 1988), which apparently resulted in the 'Little Ice Age' in Europe and the North AtlanticRegions, illustrates a changing Sun and the potential solar irradiance fluctuations. These research themes (which? Flow not clear.), addressed by VIRGO II+ are a major component of the aim of the Solar Dynamic Observatory mission and also of NASA's Living with a Star strategic plan.

Scope of Investigation: VIRGO II+ will examine the mechanisms by which energy is stored and luminosity modulated in and by the solar convection zone. The Sun's fundamental energy source is the nuclear conversion of H to He in the core. Given the long photon diffusion time scale of the order of a million years from the interior to the outer boundary of the core, there is no doubt that the energy production cannot influence the solar output. However observations show that the solar output varies globally as well as locally and hence there must be an intermediate reservoir. There are different possible mechanisms for storing energy over time scales of years and all of them perturb the equilibrium stellar structure in a distinct way which may change the solar radius (e.g. Lydon & Sofia 1995; Sofia 1998). Thus, determination of the solar radius as well as simultaneous solar irradiance observations will reveal the physical mechanisms responsible for variations of the solar energy output.

Instrumentation: The VIRGO II+ package includes the LOI+ which is a copy of the SOHO/LOI imaging telescope but equipped with a new 1000 × 1000 APS detector. The telescope is designed in an optically straightforward way and uses a spectral filter which selects a region in the spectrum which is dominated by the continuum. This simple design avoids most limiting factors encountered for measurements of solar radius and shape changes with an instrument like SOHO/MDI. The total solar irradiance are observed by two absolute radiometers as in SOHO/VIRGO, DIARAD and PMO6-V (so no new type of radiometer, as considered at a certain point in time and argued for by Claus in his Nature paper – that's a pity). The spectral irradiance is measured at three selected wavelengths with the same 3-channel filter radiometers as in SOHO/VIRGO, possibly with other wavelengths, in relation to LOI+.

Measurements: VIRGO II+ on SDO will trace luminosity variations from the base of the convection zone up through the photosphere (HOW?? LOI+ will only measure intensity variations in the photosphere. I think that needs to be explained so that the non-expert can understand the data products and how these data will yield information about the convection zone.) during the six year mission from the next activity minimum to the following maximum. By observing small changes in the solar interior structure caused by the solar cycle, we can investigate the physical mechanisms governing luminosity and radiance changes. Accurate total irradiance measurements and photometry will detect magnetically induced entropy fluctuations on daily and longer time scales as well as the solar oscillations on time scales of hours. VIRGO II+ may be able to finally detect and identify low frequency oscillations, such as low order p and g modes.

VIRGO II+ team: The investigation team is very experienced and comprises most of the VIRGO team members. The team is well-qualified to realize all aspects of the experiment. This includes defining the scientific program, prioritizing objectives, quantifying observing requirements, projecting realistic instrument performance, updating the instruments to improved performance, operating the instruments on-orbit, and analyzing and interpreting the scientific data for both solar physics and climate studies. The PMOD/WRC takes the lead for the modification of the VIRGO II+ package supported by the other hardware institutes and in particular by the ESA Research and Scientific Support Department ~~Space Science Department~~ that is responsible for the modification of the LOI to the VIRGO II+/LOI+.

We expect a broader science community to be involved in much of the analysis and interpretation of the VIRGO II+ data set and therefore, we will implement an open data policy. The VIRGO II+ data will be collected and stored at the VIRGO Data Center at the Institute of Astrophysics (IAC) at Tenerife, Spain.

1.2 Statement of the Problem

Why does the solar luminosity vary and could it change on human timescales by enough to affect terrestrial climate? As important as these questions are we do not have answers because we do not know the physical mechanisms responsible for the solar cycle with sufficient clarity to predict even the well-observed global-scale solar magnetic field evolution.

Our understanding of solar luminosity and irradiance evolution rests largely on a foundation built from many years of correlative modeling of irradiance proxies (most accurately obtained from space). Only a few limited, direct observations with the needed high spatial resolution and high photometric precision have been obtained to directly assess physical solar models. There are fundamental limitations to correlative studies which use proxies for physically important observables. For example, such efforts cannot generate answers to questions such as: "Could the solar irradiance vary by more than 0.1% over decades or longer (centuries to interglacial) timescales?" This problem obviously has implications far beyond academic questions related to stellar astrophysics.

Although the Sun supplies the energy for the Earth's atmosphere and climate systems, the measured 0.1% level of the long-term total irradiance variations are thought to be too small to cause changes in the Earth's climate above its intrinsic noise. Yet, there are tantalizing hints that the solar variability affects climate change (Hansen et al. 1993; Lean et al.1995; Crowley & Kim 1996; Reid 1991; 1997; White et al. 1997; Solanki & Fligge 1998). Other solar-type stars tend to have a higher level of variability, suggesting that the Sun's fluctuations during the last two decades may be anomalous or even temporary (e.g. Nesme-Ribes et al., 1994; Zhang et al. 1994; IPCC 1995 Report). Clearly, accurate future irradiance predictions depend on a physical understanding of the underlying mechanisms of the stellar variability mechanisms. An informed perspective on climate change and an assessment as to whether irradiance variations will affect the Earth depends on a better understanding of the solar luminosity fluctuations.

VIRGO II+ will investigate how changes in the solar interior affect energy flow from the radiative and convection zones out through the photosphere. VIRGO II+ will reveal deep solar interior changes while addressing several long-standing astrophysical problems:

- measurement of small changes in the solar radius and shape to probe minute variations in the solar gravitational potential and interior stratification,
- the measurement and exploitation of the low-frequency gravity and Rossby wave branches of the solar oscillation dispersion relation with a sensitivity that is at least an order of magnitude greater than previous studies,
- the visualization of solar cycle changes that develop near the base of the convection zone, and
- expansion of our understanding of the long-term solar variability, by incorporating sensitive photometric irradiance measurements from the absolute radiometer and filter radiometer instruments with previous total solar irradiance data.

1.3 Science aim

We have divided the observational tasks into seven parts below. Task divisions are motivated by distinct scientific questions and by the technical capabilities of the instrumentation. The key questions which VIRGO II+ will address are:

1) SOLAR RADIUS: Does the sun's radius vary over the stable timescale of the SDO mission? Between eclipse periods of the spacecraft we expect to have a radius measurement accuracy of about 1 milliarcsec and on longer timescales we can measure 10 milliarcsec radius changes. This is a very challenging goal. Is it feasible?? Compared to SOHO in its benign orbit, SDO will be a very noisy and "dirty" platform, with significant temperature variations during its orbit and eclipses which will cause SIGNIFICANT temperature disturbances. Have you considered an active heating of the front filter ring to limit these disturbances. MDI has shown that such temperature variations can cause significant instrumental effects (change of effective focal length of telescope etc.) Since we put now so much emphasis on the astrometry aspects of VIRGO-II+, we must give some thoughts to these issues. If we don't have good answers, perhaps we better give the proposal a different pitch. The detection of radius

changes allows us to understand how and where the solar luminosity is gated or stored in the radiative or convection zone?

2) SOLAR SHAPE: Do the solar quadrupole and hexadecapole shape terms vary with the solar cycle and are higher angular order shape terms of significant amplitude? How does the time evolution of the gravitational potential affect our understanding of the convection zone?
3) LATITUDE SURFACE BRIGHTNESS DEPENDENCE: Does the approximately 1K solar latitudinal surface brightness variation change with the solar cycle as predicted by earlier helioseismic solar asphericity determinations? How is this change driven by the solar dynamo and how does it change the total and spectral irradiance?
4) LOCAL BRIGHTNESS CHANGES: On solar rotation timescales, do transient quiet photospheric surface brightness changes predict future photospheric magnetic structure, as some models suggest based on thermal or ``antithermal'' shadows caused by evolving magnetic structure from near the base of the convection zone?
5) SOLAR IRRADIANCE: What is the spectral distribution of total irradiance variability? How do the transient surface brightness changes affect the total and spectral solar irradiance? To what extent are short- and long-term irradiance changes accounted for by surface magnetic activity, versus the global changes described in (1), (3) and (4) above?
6) LOW FREQUENCY HELIOSEISMOLOGY: Can the stellar r- or g-mode dispersion relation be measured from the limb displacement time series -- thereby confirming and extending the marginal r-mode identification obtained using SoHO/MDI, and providing a new diagnostic of the dynamic properties (differential rotation and global-scale flows) in the solar convection zone? By combining limb data with the irradiance and LOI$^+$ observations can we uniquely identify p-modes of very low order -- thereby accurately measuring thermodynamic conditions below the radiative/-convection zone boundary?
7) ENERGY AND ENTROPY TRANSPORT: How do magnetic fields near the photosphere and in sunspots and faculae perturb the sun's emergent energy flux or affect the transport of entropy near the photosphere? Astrometric and photometric data of the Sun at this spatially resolved precision have never before been obtained, but are critical for addressing the physical mechanisms for entropy transport near the top of the magnetized convection zone.

Solar Radius

Key Scientific Questions

- Does the Sun's radius vary over a time scale of a year at the level of 0.1. milliarcseconds?
- Can these changes be used to understand how and where the solar luminosity is gated or stored in the radiative or convection zone?

Observations of the TSI, helioseismic studies, and precise solar photometric measurements all show that the Sun varies globally, as well as locally at the photosphere, during an 11-year solar cycle. Only very recently have helioseismic studies empirically shown that much of the Sun, at least from the top of the interior radiative zone to the photosphere, participates in the solar cycle (Howe et al.

2000). The Sun's likely solar cycle energy storage mechanism (e.g. gravitational or magnetic fields) will change its radius (e.g. Dearborn & Blake 1980; Spruit 1982; Lydon & Sofia 1995; Sofia 1998) with an amplitude which is characteristic of the depth and nature of the perturbation. Thus, sensitive radius measurements will greatly improve our ability to isolate and understand the changes in the interior structure caused by the solar magnetic/luminosity cycle.

While ground-based measurements of the solar radius exist over the last 300 years exist (e.g. Ribes et al. 1991), the results are neither consistent nor conclusive. Historical data show that the sun's radius may have been larger during the Maunder Minimum, which coincided with extremely cold periods in Europe and the Atlantic regions (Ribes et al. 1991). These results are also suggested by the French CERGA radius measurements which found a larger solar radius during solar minimum (e.g. Laclare et al. 1996; Pap et al. 2001). In contrast, Ulrich and Bertello (1995) found a positive correlation between apparent radius changes and the solar activity cycle. There are also hints of periodic solar radius variations over time scales of 1,000 days to 80 years (Gilliland, 1980), but the measurements are generally neither consistent nor conclusive (Parkinson et al. 1980; Brown, 1987; Ribes it et al. 1991). These controversial results underscore the necessity of more sensitive efforts to measure the sun's radius. The limitation of ground-based measurements due to ‘seeing’ from the Earth's atmosphere has also been recognized by Sofia and his collaborators in their development of the balloon borne Solar Disk Sextant (Sofia et al. 1994).

The MDI experiment offered, for the first time, the promise of very accurate solar radius measurements obtained from space. Figure 1 shows the residual MDI radius determination after correcting for the apparent variation due to the SoHO orbit. Residual instrumental errors due to a small yearly solar heating variation of the MDI front window, and larger ``jumps'' due to internal focus optics changes within the instrument are apparent. After correcting for these errors using an empirical thermal model for the front window, we recovered the radius measurements shown in Fig. 2. The unmodeled linear residual radius change is about 0.008 arcsec/year, but because of the MDI instrument limitations we must treat this as the systematic measurement uncertainty and an upper bount to possible cyclic or secular solar cycle variations. The MDI measurements represent the most sensitive observation of possible solar radius changes that have been obtained, but they do not have sufficient accuracy to detect solar cycle variations.

In contrast to MDI, the LOI$^+$ instrument we propose here has a simple and stable optical configuration. We expect it to achieve astrometric accuracy comparable to MDI and the relative radius measurements to be more accurate than those of MDI. Because the wavelength setting of LOI$^+$ at 665 nm is not near and in Fraunhofer lines, its photometry is insensitive to velocity and magnetic field contamination.

VIRGO II$^+$ Task 1 – SOLAR RADIUS

Radius measurements with an rms accuracy of 1 milliarc over a timescale of one solar rotation period (27 days) are required. Peak-to-peak systematic radius errors will be smaller than 10 milliarcsec over the mission duration.

Some stellar model calculations suggest that a deeply seated solar luminosity perturbation with an amplitude of 4×10^{-4} can cause approximately a 10^{-6} fractional change in the photospheric solar radius. It may be possible to detect this change with a measurement accuracy of 1 milliarcsec. The temporal resolution of these measurements should be at least one solar rotation, although faster radius changes are physically possible and the baseline operation mode should allow this.

Solar Shape

Key Scientific Questions

- Do the solar quadrupole and hexa-decapole shape terms vary with the solar cycle?
- Are higher angular order shape terms of significant amplitude?
- How does the time evolution of the gravitational potential affect our understanding of the convection zone?

The theory of the solar limb shape is well established, although current solar shape measurements (also from MDI astrometry) are marginally inconsistent with the shape deduced from the helioseismic solar interior rotation determinations (Armstrong & Kuhn 1999). This is an important problem since the limb shape is a sensitive function of the sun's gravitational potential and its interior rotation. Thus, the measurement of solar cycle changes in the shape is another important tool for seeing how the solar magnetic cycle causes global changes in the solar interior stratification and dynamics.

Only two high order shape experiments (Lydon & Sofia 1996; Kuhn et al. 1998) have been successful, and they were not consistent. Since these data were obtained at different phases of the solar cycle, they suggest a temporal variability in the solar hexadecapole term. In order to reconcile the solar interior mass and rotation models with the observations, we require shape data that allow the possibility of measuring temporal solar cycle variations.

Progress on this problem depends on measurements obtained with a single instrument over several years. VIRGO II^{+} will be launched during an optimum part of the solar cycle for this purpose. The most accurate shape measurements are obtained when solar activity does not obscure the photosphere. The SDO mission is launched when the solar activity will still be low when sunspots and faculae will not dominate the limb shape measurements. Our experience with MDI proves that during this phase of the cycle we will be able to study both the deeper interior changes, whereas we also are sensitive to and can follow the increasing surface activity up to the maximum. While we cannot be certain at what level the gravitational potential or the rotational interior stratification changes will occur at, the evidence from MDI and the known shape-model discrepancies imply that limb coefficient measurement accuracy of better than 0.1 milliarcsec will either establish or refute the hexadecapole variations while extending limb shape measurement sensitivity into a regime where physical changes may be expected.

VIRGO II^{+} Task 2 – SOLAR SHAPE

Angular harmonic limb shape terms of order 2 – 20 will be measured with a precision of 0.1 milliarcsec rms on solar rotation timescales. This requires occasional rotation of the instrument with respect to the Sun-pointing direction in fixed increments of 9 degrees, in order to calibrate and correct for the instrumental distortion.

The required solar limb shape accuracy is driven by the need to establish or refute hints from other measurements that the gravitational potential varies. The duration of a composite shape measurement which consists of individual limb measurements at various roll angles must be no longer than a few hours because of the requirements imposed by the phase demodulation technique used to separate instrument shape noise from the solar signal (Kuhn et al. 1998). The timescale for global potential changes is long, so that multiple measurements, at least over solar rotation timescales, can be combined.

Solar Irradiance & Brightness Variations

Key Scientific Questions

- What is the spectral distribution of total irradiance variability?
- How do the transient surface brightness changes affect the total and spectral solar irradiance?
- To what extent are short- and long-term irradiance changes accounted for by surface magnetic activity, versus the global changes, such as those of radius and temperature?
- Does the approximately 1K solar latitudinal surface brightness variation change with the solar cycle as predicted by earlier helioseismic solar asphericity determinations?
- How is this brightness change driven by the solar dynamo?
- On solar rotation timescales, do transient quiet photospheric surface brightness changes predict future photospheric magnetic structure, as some models suggest based on thermal or 'antithermal' shadows caused by evolving magnetic structure from near the base of the convection zone?
- How does the non periodic solar background signal change with solar activity and solar latitude?

Relative changes in the total solar irradiance (TSI) have been precisely measured for more than two decades by several space experiments, such as the Nimbus-7/HF, SMM/ACRIM I, UARS/-ACRIM II, ERBS, EURECA/SOVA, SOHO/-VIRGO and most recently by ACRIMSAT (Fig. 3).

These measurements show that TSI varies over the solar cycle by 0.1%., being higher during maximum activity conditions (Willson & Hudson 1988). Short-term changes on scales of days to months are mainly attributed to the effect of active regions as they evolve and move across the solar disk (Chapman 1987; Fröhlich & Pap 1989). On time scales of minutes to hours, the variance is determined by granulation and supergranulation and in the 5 min range by the p-modes (Fröhlich et al. 1997a). On yearly or solar cycle time scales irradiance variability could be related to changes of the solar luminosity directly (e.g. Lydon & Sofia 1995; Kuhn 1996; Lydon et al. 1996).

While considerable descriptive information exists on solar irradiance variations, we lack consistent physical models for the observations. For example, it has been shown that empirical irradiance models based solely on a 'tally' of the surface manifestations of magnetic activity cannot explain all TSI changes (Fröhlich & Pap 1989; Kuhn 1996; Pap 1997; Fröhlich et al. 1997a; Wehrli et al. 1998). Wouldn't it be appropriate to quote some of the papers by Solanki & Fligge? If you believe that they have shortcomings, name these! But they should be mentioned somewhere.The identification of the residual variability is a difficult problem since many mechanisms may affect the total irradiance and luminosity. These mechanisms range from photospheric temperature changes (Kuhn et al. 1988), convective cells (Ribes et al. 1985), large scale mixing flows (Fox & Sofia 1994) to radius changes (Delache et al. 1986; Ulrich and Bertello 1995; Kuhn et al. 1997; 1998). Very high precision photometric and astrometric data with spatial resolution over a significant portion of the activity cycle are needed to disentangle these sources in the TSI variance.

Resolved surface brightness measurements are often limited, not by instrumental photometric accuracy, but by the modulation of intrinsic spatial intensity gradients (e.g. limb darkening) and instrumental spat~~c~~ial, or registration uncertainty. Thus, to achieve high differential (or relative) photometric precision requires corresponding astrometric precision. Solar limb observations, which provide a fundamental fiducial when analyzed for both astrometric and photometric variations, will yield the most precise measurement of large scale solar differential surface brightness variations.

Recent precision limb brightness measurements from MDI are reproduced in Fig. 4 (expressed as an effective temperature variation). These were obtained from MDI during a 10 hour period in March, 1997 when SoHO was rolled in increments of 30 degrees. These data were obtained near the minimum in the solar activity cycle and MDI magnetograms confirm that there were no sunspots and virtually no significant magnetic field regions on the limb or disk. When seen with this photometric accuracy the solar limb data show dramatically that the surface brightness of the sun is not constant, and importantly, not determined by faculae and sunspots. One solar cycle earlier groundbased observations were just barely able to resolve this large scale latitudinal brightness variation using a full 4 month observing season (Kuhn et al. 1985).

The temporal and spatial resolution possible with space experiments reveals new (and apparently fundamental) features of the solar convection zone. For example Fig 4 shows a striking dip in the temperature of the extreme south pole (the Sun's north pole was not visible to SOHO at the time of these measurements).

SDO/VIRGO II$^+$ will allow snapshot observations of higher angular resolution and greater photometric dynamic range throughout its 6 year mission than was available from MDI. We will see the dynamic evolution of entropy perturbations from the base, and throughout the convection zone. Entropy 'shadows' (Parker 1995) or 'antishadows' (Kuhn & Stein 1996) of magnetic changes occurring at the top of the solar interior radiative zone will be revealed from these extremely precise photometric views of the limb. Again, to me this sounds very challenging. I believe some more words would be in order as to how we want to achieve this. Models, which explain how the solar luminosity is gated by interior magnetic fields as it diffuses and convects to the photosphere, will be directly tested by the VIRGO II$^+$/LOI$^+$ limb photometry.

VIRGO II$^+$ Task 3 – LATITUDE SURFACE BRIGHTNESS DEPENDENCE

Limb brightness observations with a relative accuracy of 5×10^{-5} will be obtained with a time resolution of a solar rotation period. This requires rotation of the instrument with respect to the Sun pointing direction in fixed increments of 9 degrees.

This requirement follows from the magnitude of the known surface brightness variations and will yield measurements of sufficient accuracy to measure the expected solar cycle changes over a 6 month time period during the ascending portion of the solar cycle when SDO/VIRGO II$^+$ operations are anticipated. The angular resolution is required to fully isolate and resolve changes in the extreme polar thermal 'dip' anomaly (cf. Fig. 4). These solar cycle brightness variations require data with a 6 month cadence. Calibration cycle data (one week cadence) can be combined to generate the required precision.

VIRGO II$^+$ Task 4 – LOCAL BRIGHTNESS CHANGES

Limb brightness observations with a relative accuracy of 1×10^{-4} will be obtained with a time resolution of 1/4 of a solar rotation period. This requires rotation of the instrument with respect of the Sun-pointing direction in fixed increments of no more than 9 degrees. In contrast with Task 3, better temporal resolution (7 days or less) but relaxed photometric precision is required. Do I understand this correctly, that the requirement is to roll the S/C every 7 days or so? I doubt that this will be an option. Having orchestrated a S/C roll just recently, I doubt that this can be done frequently. This task uses the same data sequence as Task 3 but addresses larger amplitude limb brightness changes that occure on active region evolution timescales.

To obtain thermal ‘snapshots" of the interior entropy perturbations the coarsest temporal sampling should be about 6 - 7 days. The angular resolution of these measurements will allow the photospheric thermal perturbations of deep magnetic fields, or emerging active regions, to be resolved in latitude and time.

VIRGO II+ Task 5 – IRRADIANCE

The SPM spectral irradiance will be obtained with a 1 min cadence during the 6 year duration of the mission. The total irradiance is available at a cadence of 2 and 3 minutes for PMO6 and DIARAD, respectively, with a short term precision of <10 ppm and long term stability of <50 ppm. Identifying magnetic and bolometeric origins of the irradiance changes requires full-disk observations with LOI+. The comparison of spatially resolved differential photometry with irradiance changes caused by magnetic features (e.g. sunspots and faculae) requires a photometric accuracy of about 0.5% for the 2 arcsec pixels of LOI+. A cadence for the full disk measurements of 10 - 12 minutes (time averaged) will be used to sample magnetic evolution timescales. Should one emphasize here the importance of continuing the 25 year record of solar TSI measurements, an absolutely critical key measurement of the Sun, which shouldn’t be interrupted under any circumstances.

Low Frequency Helioseismology

Key Scientific Questions

- Can the stellar r- or g-mode dispersion relation be measured from the limb displacement time series – thereby confirming and extending the marginal r-mode identification obtained using SOHO/MDI, and providing a new diagnostic of the dynamic properties (differential rotation and global-scale flows) in the solar convection zone?
- By combining limb data with the irradiance and LOI+ observations can we uniquely identify p-modes of very low order – thereby accurately measuring thermodynamic conditions below the radiative/convection zone boundary?

Coherent long period oscillations are more readily detected from shape observations than from Doppler measurements. At low frequencies solar Doppler data are dominated by the incoherent velocity noise from the convection zone. On the other hand, at low temporal frequencies even a low velocity oscillation can be extracted from the convective noise in an astrometric measurement. This is because the limb displacement amplitude grows linearly with oscillation period (for a constant velocity amplitude) while the astrometric convection noise contributes only incoherently on shorter timescales. Thus, the most sensitive measurement of low frequency solar oscillations (periods longer than about 1-2 hours) comes from the MDI limb shape time series. Figure 5 shows the mean temporal limb displacement oscillation spectrum, converted to an equivalent rms velocity amplitude spectrum.

The broad power ``bump" in Fig. 5 corresponds to periods near 11 hours and is not likely to be caused by low order g-modes since they more efficiently penetrate the convection zone to reach the photosphere at periods of one to a few hours (Kumar et al. 1996). The most likely cause for the observed excess power at the lowest frequencies is solar r-modes ('Rossby modes'). These are nearly incompressible low frequency oscillation modes which are driven by Coriolis forces in a rotationg star. The possibility of such long period oscillations, which are likely to be mode-locked with the rotating photosphere, was first suggested by Wolff (1974, 1998). Phase coherence of the MDI limb displacement power spectrum at low frequencies supports this interpretation (Kuhn et al. 2000) but the higher sensitivity observations from VIRGO II+ will allow us to measure the r-mode properties. With the r-mode 'k-ω' dispersion relation we will have a new tool for directly inferring the convection zone rotation and large scale interior flows (Wolff 1998).

Solar gravity modes hold the key for understanding the deepest interior conditions of the sun (Gough 1994). Their detection will empirically reveal the thermodynamic conditions in the energy generating core of the Sun, and the central boundary condition for the solar luminosity. From the low frequency data of the MDI and VIRGO experiments on SoHO no g-modes or very low order p-modes could be detected, only an upper limit was stated by Appourchaux et al. (2000). As the solar noise in irradiance observations increases more slowly towards low frequencies than in the velocity signal and by combining SPM and absolute radiometer data with the LOI+ limb data we will improve the detection threshold for low order p- and g-modes with periods between 20 minute and 1hour.

At periods of 1 - 2 hours the most sensitive detection limit on g-modes was demonstrated by MDI (Fig. 5). It is also in this frequency regime that we expect the greatest improvement in the MDI noise background from VIRGO II+. While we do not know the actual surface amplitude of solar g-modes, there are suggestions (Kumar et al. 1996) that low order modes could have amplitudes near 0.1 mm/s. For angular harmonics higher than 4, VIRGO II+ will achieve an instrumental sensitivity of 0.05 mm/s over its 6 year lifetime. If solar noise sources do not dominate, then VIRGO II+ may yield the first detection of bouyancy waves (g-modes) in the Sun.

Our experience with MDI indicates that the instrumental noise limitations of VIRGO II+ data are likely to result from: 1) residual flat-field calibration errors, and 2) time series interruption and contamination from other instrument and spacecraft experiment requirements. For angular harmonics larger than l = 3 and at frequencies higher than 30 μHz MDI achieved an astrometric noise power density which was within a factor of two of the estimate based on flat-fielding noise and the pixel size. The VIRGO II+ instrument noise background power density will be significantly lower than MDI at low frequencies. The simpler optical design of LOI+, improvements in flat-fielding, and noise reduction from satellite system contamination will reduce the higher frequency astrometric noise by more than one order of magnitude over MDI. That needs to be demonstrated in the following (instrument) sections!! Again, keep in mind the difference between the benign SOHO orbit and the messy SDO orbit!

The VIRGO II+ astrometric oscillation time series should yield a completely new probe of the solar convection zone. The likely measurement of r-mode dispersion, and the possible detection of solar g modes, opens new windows into the sun. As the VIRGO II+ data become available, we expect that it will stimulate scientific activity in the new field of 'low frequency helioseismology'.

VIRGO II+ Task 6 – LOW FREQUENCY HELIOSEISMOLOGY

The data from VIRGO, MDI and GOLF on SOHO as well as ground based networks have shown that Doppler shift measurements are superior to radiance/irradiance measurements in the delectability of low frequency p-modes. This is due to the fact that the frequency dependency of the solar background signal ("solar noise") increases more slowly with decreasing frequency for the p-mode range in Doppler measurements than in radiance. This is most certainly the case down to a frequency of 150µ~~μ~~Hz, but may not be true at lower frequencies. There are indications that instrumental noise may be a significant contribution to VIRGO data in the 20 – 60 µHz region. This may, at least partly, be caused by the readout chain of the data, this will be designed differently in the instrument proposed here. So currently we do not know the detailed shape of the solar noise spectrum in this region. This will be measured by the proposed investigation.

The ratio of the vertical to horizontal displacements in solar oscillations change with frequency, the p-modes being predominantly vertical and the lowest frequency g-modes mostly horizontal. This will clearly influence the amplitude of the different modes at the limb. But the solar background signal will also change at the limb. At medium to low frequency the major source of solar noise will be the supergranulation signal. This is dominated by horizontal motions at the surface and will therefore a significant source of noise in Doppler measurements at the limb. Even for direct measurements of solar oscillations at these frequencies at the limb there is evidence that radiance measurements may be better than Doppler shift measurement.

VIRGO II^{+} will obtain time series of limb brightness, limb displacement, and irradiance observations with a cadence of 1 min and a duration of 6 years. The limb intensity and displacement will be determined in 512 position angle bins with a limb displacement accuracy of 5 milliarcsec per bin per measurement. This per pixel limb displacement accuracy requires a detector with 2 arcsec pixels. In addition, the SPM data will provide parallel measurements with a 1 min cadence. The instrumental noise of both SPM and LOI^{+} is below 0.03 ppm in the 5-minute range and increases towards lower frequencies as 1/f. At intermediate frequencies (periods less than one hour) the comparison of the limb oscillation data with the intensity oscillations data will allow the assessment of low frequency p-mode oscillations (and possibly g-modes).

The quoted astrometric accuracy is required to unambiguously identify the low frequency r-mode oscillation spectrum (again, how will we achieve that – needs to be demonstrated!). These data will also reduce the background noise power near 100 µHz to an equivalent velocity amplitude of less than 0.1 mm/s. According to some calculations (Andersen 1996; Kumar et al. 1996), g modes may be visible with this sensitivity.

Energy and Entropy Transport

Key Scientific Questions

- How do magnetic fields near the photosphere and in faculae and sunspots perturb the Sun's emergent energy flux?
- How do magnetic fields affect the transport of entropy near the photosphere?

Solar astrometric and photometric data at this spatially resolved precision have never before been obtained. These data are critical for addressing the physical mechanisms for entropy transport near the top of the magnetized convection zone (how? Think we should elaborate a bit on how we would actually get this information) and to clarifying surface magnetic activity's contribution to the observed changes in solar luminosity.

Magnetic structure in the photosphere perturbs the steady convective and radiative heat transport from the interior. The total energy budget of sunspots, faculae and active regions is also not well underrstood. For example, we know that surface magnetic fields are associated with both positive and negative irradiance changes, depending on the timescale. On short times scales (<60 days) magnetic fields decrease the irradiance, while on longer times scales an increase in the photospheric magnetic flux increases the irradiance. The effects of faculae and sunspots on the Sun’s luminosity (its total energy integrated over all angles) and its irradiance (the energy radiated into the ecliptic plane) are likely very different. We need long time series of precise photometric measurements of solar active regions as they rotate from limb to disk-center to solve simple questions like, “Does an active region change the solar *luminosity* differently than its effect on the *irradiance*?”

Longstanding problems like, “Why does the Sun rotate differentially?” depend on understanding how the solar convection zone transports flux from the interior. Careful observations of excess or missing flux around sunspots and active regions show how anisotropic the effective solar conductivity really is. We will use these data to construct global models of the energy flux circuit in the Sun. Such studies will finally allow us to make realistic comparisons between what we learn with small scale numeric solar exeriments, our most important tools for understanding convection, and the global solar luminosity problem.

VIRGO II$^+$ Task 7 –
ENERGY AND ENTROPY TRANSPORT

Full disk observations with 2 arcsec pixels, in 0.2 nm bandwidth in the continuum at 665 nm wavelength, with at least a 12 min cadence, and 0.5% photometric accuracy are required. Temporal low-pass filters must be applied to reduce the effects of 5-min oscillations on the full-disk photometric data.

Continuous temporal coverage with approximately 12 min cadence will be used for studies of entropy perturbations in the convection zone due to surface magnetic fields. With these data we will observe the emergent radiation as it varies due to solar rotation and the evolution of photospheric fields. The exploration of, for example, the transport properties of the Sun's convection zone (in particular task 7) is likely to occupy researchers for several years.

1.4 Relevance to NASA's “Living with a Star” Program and the Solar Dynamics Observatory

The “Living with a Star” (LWS) program, managed by the Sun-Earth Connection Division of the Office of Space Science within NASA, will address various aspects of the Sun-Earth system that affect life and society. The purpose of LWS is to increase our understanding of the origins of geo-effective space weather and climate through basic research into the relevant physical processes on the Sun, in interplanetary space, and in the near-Earth environment. The first element of the LWS program is the Solar Dynamics Observatory (SDO). The primary goal of the SDO mission is to understand --ideally predict-- solar variations and their effect on Earth by determining 1) how the Sun's magnetic field is generated and structured, 2) how stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in solar irradiance.

The Living with a Star program is the result of dedicated studies of solar events over the last centuries to the modern satellite era. Ever since the earliest telescopic observations, the solar variability in the form of sunspots and related magnetic activity has been the subject of careful study. High precision photometric observations of solar-type stars clearly show that year-to-year brightness variations connected with magnetic activity are a widespread phenomenon among such stars (e.g. Radick 1994). As the nearest star, the Sun is the only star where we can observe and identify a variety of structures and processes which lead to irradiance variability on time scales from minutes to decades. High spatial and temporal resolution observations conducted by various experiments on the SOlar Heliospheric Observatory (SOHO), along with other space observations, like YOHKOH and TRACE, and also from the ground, have demonstrated that the surface of the Sun and its outer atmosphere are highly dynamic on almost all spatial scales.

In conjunction with these solar imaging experiments, the Sun's radiative output has also been monitored at various wavelengths over the last two and half decades. The 'Variability IRradiance and Gravity Oscillations' (VIRGO) experiment on SOHO has been measuring solar irradiance in the entire solar spectrum and at specific narrow wavelength bands in the near-UV (402 nm), visible (500 nm), and near-IR (862 nm) since 1996 (Fröhlich et al. 1997). While the VIRGO spectral observations are the first continuous space observations in the visible and infrared, the VIRGO total irradiance measurements have provided an important segment of NASA's long-term irradiance data base for climate studies. The VIRGO measurements, along with other irradiance monitoring experiments, have demonstrated that solar irradiance varies on time scales from minutes to years, confirming that our Sun is indeed a variable star.

Studying the Sun's variability is important for both solar physics and solar-terrestrial physics. Even tiny changes in total solar irradiance give us information about the internal processes by which energy is transported from the core, while analyses of spectral irradiance observations from UV to infrared help us to understand the changes taking place in the photosphere and chromosphere. In addition to the solar physics aspects, the terrestrial implications of solar irradiance variability are equally important. Since the Sun's radiative output establishes the Earth's thermal environment, knowing the source and nature of its variability is essential to understanding and predicting the interactions in the Sun-Earth system, which in turn are vital for assessing the impact of human activities. We are concerned with three major questions: How does irradiance variability originate in the Sun? How does variability in solar radiation influence Earth's atmosphere and climate? How does the changing Sun influence our space environment and human activities in space? These 3 key questions are NOT addressed adequately in the previous sections (7 "themes" or "aims"). But these 3 questions are the key issues of SDO. That's what LWS is all about! So are we missing something here?

The Earth's climate is the result of a complex and incompletely understood system of external inputs and interacting parts. Climate change can occur over a range of time scales, either as a consequence of natural variability – including solar variability – and/or anthropogenic causes and may be identified through the study of a variety of measurable parameters. One of these parameters is the solar energy flux at various wavelengths. Therefore, accurate knowledge of the solar radiation received by Earth, as well as an understanding of its variability, are critical to an informed perspective on climate change and the climatic response to increasing greenhouse gas concentrations. On the other hand, space weather is in its broadest sense a science dedicated to understanding the full range of external physical phenomena which affect the Earth and its environment. By far the most important driver of the 'local' day-to-day space weather is the Sun and its highly variable short wavelength electromagnetic and particle emissions which may directly affect human activities in space and on ground. Can be deleted, I think.

While the space weather implications of irradiance variations will be addressed by the 'Spectrometer for Irradiance in the EUV (SIE)' (what has SIE to do with space weather??) experiment, the VIRGO-II-Plus experiment will provide an important segment of the LWS science objectives, addressing the question: "How solar variability may influence climate?" This is also the objective of SIE!! Not just VIRGO-II+!It must be emphasized that despite the efforts put forward to measure and analyze solar irradiance variations over the last two and half decades, we still lack a self-consistent theory which explains why the solar irradiance and luminosity vary with the magnetic cycle. In addition to maintain high precision and long-term irradiance measurements, we need sharper tools to describe and understand the sun's global aspheric response to its internal dynamo, and we need to be able to measure the solar cycle manifestation of the magnetic cycle on entropy transport from the interior to the photosphere in much the same way that we study the fundamentally more complex problem of magnetic flux transport from the solar interior.

We underscore that the SDO Science Definition Team (SDT) acknowledged the importance of total solar irradiance measurements. According to the SDT report, Chapter 4.9, p. 39: "The total solar irradiance must be accurately and precisely monitored to determine the nature and source of the irradiance variations (Section 3.1.1.2). These observations are of highest priority to SDO but will likely be obtained from both SORCE (Section 7.4) and GOES/NPOESS (Section 7.5) during the SDO mission and are therefore not included as part of SDO. If, however, it appears that these observations will not be provided by these alternative sources then a Total Solar Irradiance Monitor should be placed on SDO." It must be emphasized that although the VIRGO II+ experiment is a complementary experiment to SORCE and NPOESS, Will there be two redundant TSI instruments out and observing or not? If yes, we have a weak case. If not, say so! it is a more complex experiment than either of them, providing not only irradiance measurements but also high resolution images to study the underlying mechanisms of irradiance and luminosity variations and thermal structures associated with magnetic field structures - which is listed also as high priority investigations, generically called "Photometric Imaging Telescope", in the SDT report. The essential goal of the VIRGO II+ investigation is to understand luminosity variations in the Sun by tracing these changes from the base of the convection zone up through the photosphere by observing small radius changes, oblatennes, hexadecapole, and higher order shape changes to probe the solar interior structure. Redundant. Can be deleted.

Relevance to SORCE and NPOESS

It must be emphasized that the VIRGO II+ experiment proposed to SDO is a complementary experiment to both SORCE and NPOESS from several points of view. On one hand, SORCE is a two year mission with a possible extension to 5 year, providing observations between late 2002 and 2007, while the NPOESS measurements will start only in the time frame of 2009 - 2011. Since at this time the SORCE follow-up mission, called as EOS-IV, has not been formally approved, the VIRGO II+ experiment on SDO has to be considered as a high priority experiment since it may provide a bridge between the SORCE and NPOESS measurements if EOS-IV is not approved or delayed. On the other hand, the SDO SDT report underlines (see Overview, p. 7.) that "a Total Solar Irradiance (TSI) Monitor" should also be included if redundant observations are not available concurrently with SDO." Considering these SDT statements, the VIRGO II+ experiment on SDO would ensure redundant total solar irradiance measurements or, in the worst scenario, it would serve as a "third-party" experiment connecting SORCE and NPOESS. It should also be emphasized that in addition to the radiometers, VIRGO-II will also carry SunPhotometers (SPM) to monitor spectral irradiance in the near-UV, visible and infrared. The SPM spectral measurements would also ensure redundant spectral irradiance measurements along with the "Spectral Irradiance Monitor" (SIM), which is part of the SORCE instrument package. These parallel total and spectral irradiance measurements on SORCE and SDO are especially important since neither TIM (not introduced yet) nor SIM had previous flight experiments.

Relevance to HMI

~~The lead~~A key element of the VIRGO II+ instrument package is an advanced version of the "Luminosity Oscillation Imager" (LOI+) which will take 1000 × 1000 pixel images at 782 nm. Observations of LOI will make it possible to understand luminosity variations in the sun by tracing these changes from the base of the convection zone up through the photosphere by observing small radius changes, oblateness, hexadecapole, and higher order shape changes to probe the solar interior structure. The VIRGO II+ experiment package will provide complementary science to the "Helioseismic and Magnetic Imager" (HMI) from several points of view. While highly precise photometry, provided by HMI, will detect magnetically induced entropy fluctuations in the deep solar convection zone from their faint thermal shadows visible at the photosphere (so all this is being done by HMI?), the VIRGO II+ will provide the full-disk calibration needed to interpret the integral of the spatially resolved photometry from HMI (so LOI+ is more or less a calibration source for HMI??). Since HMI provides only accurate differential photometry, we can rely on full-disk VIRGO II+ data to diagnose the temporal stability of HMI photometry. The very accurate limb photometry and astrometry from LOI+ give critical wavelength dependence information for interpreting the HMI photometry. Once again the spectral signature derivable from the combination of HMI photometry and LOI-Plus may be used for distinguishing physical irradiance mechanisms. These combined studies by VIRGO II+ and HMI will enable us to replace the current empirical models to construct irradiance variations back to the time of the Maunder Minimum and predict future solar-induced climate changes – a research effort which requires complementary experiments and is one of the centerpiece of the LWS program of NASA.